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IMAGING THROUGH FIBERS, PHASE 2

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13. ABSTRACT *(Maximum 200 words)*
This Phase 2 effort demonstrated the transmission of an image using a single-mode fiber for the image and a second single-mode fiber for transmission of the reference beam. The prior Phase I effort transmitted the reference beam through free space. An acousto-optic cell provides a temporally incoherent source, from a spatially coherent reference input, that illuminates an object. The light is then transmitted through a lens to the back focal plane where the Fourier transform is observed. A single mode fiber, on-axis, at the back focal plane transmits the light to the receiving location. The reference input is transmitted through a second fiber to a second acousto-optic cell synchronized to the first. The two beams are mixed at the receiver, and the image is recovered by computer processing. Thus, the input spatial frequency components are translated to temporal frequencies and then back again. Three dimensional images were recovered with resolution near the theoretical limit.

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Introduction

This phase 2 contract called for a continuation of the work on phase 1. In phase 1, we demonstrated the transmisson of an image over a single fiber using the process of holography,[1] with the reference beam propagated over free space. In phase 2 a number of extensions were proposed, the primary effort being to demonstrate the transmission of an image over a single, single-mode fiber, with the reference beam being similarly confined to a single, single-mode fiber. This task was accomplished, and the results were successful

Background

The theory was previously demonstrated in the phase 1 contract by transmitting an image over a single 12 micrometer multimode fiber, with a free-space propagated reference beam. In phase 2 we used a single-mode fiber, and we also confined the reference beam to a single fiber. Thus, we have transmitted a complete image, both phase and amplitude, over a pair of single-mode fibers

The basic idea is explained with the aid of Fig. 1. Light from a monochromatic spatially incoherent source, generated for instance by running an expanded laser beam through a moving diffuser, illuminates an object. If the illuminating source had been spatially coherent (a single plane wave) then the object Fourier transform would be formed at the back focal plane of lens L_1 (plane P_3). Noting that the entrance end of the fiber is also positioned in plane P_3, and assuming the fiber to be on axis and the illuminating plane wave to be propagating down the z axis, the zero spatial frequency (or DC) component of the Fourier transform would pass through the fiber. Of course, many Fourier components are required to form an image, and they must all be combined with the proper phase relationships.

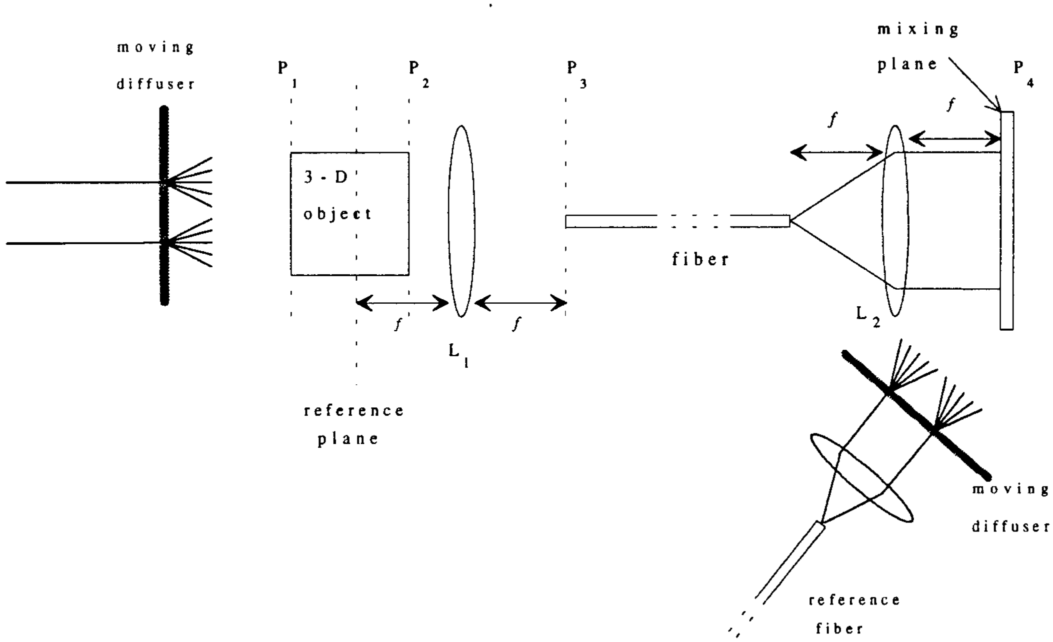


Fig. 1. System for transmitting 3-D images through single-mode fiber.

We note that the incoherent source can be viewed as a collection of mutually incoherent plane waves with different spatial frequencies. This becomes evident when we take the diffuser to be a random phase grating. Allowing the diffuser to be stationary, the illuminating plane wave, upon propagation through the diffuser, will generate a continuum of plane waves with a certain phase relationship. As the diffuser moves, the phase of each individual plane wave will vary with time in a random manner, thereby broadening its temporal bandwidth and making the set of plane waves mutually incoherent, assuming the integration time to be long relative to the diffuser motion.

Now each component plane wave of the incoherent source projects a Fourier transform to plane P_3. The Fourier transforms are displaced from each other in accordance with the spatial frequency of the source plane wave component. Each spatial frequency element thus shifts a different object spatial frequency component to zero, whereby all object spatial frequency components get coupled into the fiber. The object spatial frequencies have been encoded as mutually incoherent temporal waveforms, or coherence elements, and transmitted down the fiber in parallel.

From the above viewpoint, the spatially incoherent source is not strictly monochromatic. However, a source with any degree of spatial incoherence cannot be strictly monochromatic; a strictly monochromatic extended source would have coherence between the different source elements. In the theoretical treatment of spatially incoherent illuminating sources, sufficient bandwidth is required so that over the detection time the correlation between light from different source elements will be zero; but also, the source bandwidth is assumed sufficiently narrow that path differences between the two interfererring beams are small compared to the coherence length of the light. A suitable source for the process described here is a He-Ne laser with a coherence length of a few cm. The temporal bandwidth broadening caused by the production of a spatially incoherent source generation method, such as propagating through rotating ground glass, is generally less than the inherent bandwidth of the laser. Hence, the process we describe here of image formation through fibers is properly described in terms of spatial incoherence effects and not on temporal incoherence effects.

In order to recover the image each temporal waveform must be decoded to its corresponding spatial frequency element. To decode the signal, a portion of the laser light is split off from the incident beam before it reaches the object-illuminating diffuser, and is transmitted via another fiber to a plane P_4. Being a monochromatic spatially coherent beam, it can be transmitted through the fiber without distortion. The beam exiting the reference fiber is then sent through a diffuser identical to the object-illuminating diffuser and having the same motion. The spatial and temporal object illumination field is hence reproduced at the receiver end of the reference branch. The two beams are brought together to form a hologram. In the recording process, each spatial frequency element of the reference beam will interfere only with the corresponding temporal waveform exiting the object branch fiber and will create a fringe

pattern of the appropriate spatial frequency. The image can then be produced from the hologram by the usual methods, yielding a 3-D complex image.

Description of Accompishments

The system we used is in essence that shown in Fig. 1, although with some modifications. The system requires spatially incoherent light, which is typically obtained by a moving diffuser. To implement the system described shown in Fig. 2 requires two identical diffusers moving in synchronism, which is impractical. An alternative method is to use acousto-optic (A-O) cells. From the spatial coherence point of view both of these methods provide spatially incoherent illumination in the sense that all the spatial frequency components generated are mutually incoherent due to their different Doppler frequency shifts.

The implementation used here involves producing one dimensional incoherent illumination via the first diffracted order of an A-O deflector driven by a swept-frequency voltage. Extension to full three-dimensional space and two-dimensional spatially incoherent illumination is straight-forward.

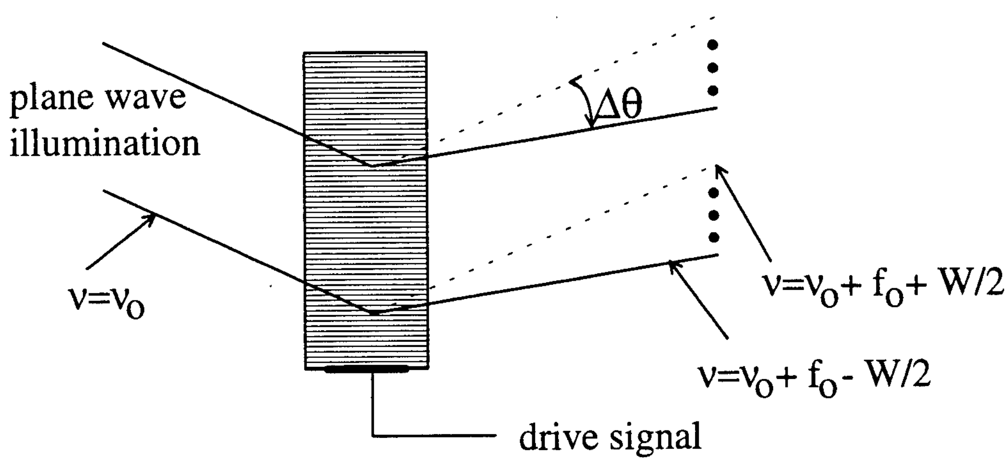


Fig. 2. Spatially incoherent source generation using an Acousto-Optic deflector. The drive signal is a chirp of bandwidth W and center frequency f_o. The input illumination is a plane wave having temporal frequency $n=n_o$. The output consists of a set of plane waves having a spatial bandwidth proportional to the A-O drive bandwidth (W). Furthermore all the plane wave elements are mutually incoherent because they have incurred different Doppler shifts having been generated by different temporal frequency components of the A-O drive signal.

The operation of the A-O cell in generating a spatially incoherent extended source is illustrated in Fig. 2. The driving voltage is swept over a frequency band W, thereby

generating a range of diffracted waves covering an angle Dq, where Dq=Wl/V_s (l is the optical wavelength in the material and V_s is the acoustic velocity in the material). If the sweep rate is sufficiently high that at any instant a chirp-like grating of bandwidth W fills the A-O aperture, which is the case we have employed here, then a set of diffracted collimated waves, each directed in a different direction (having a different spatial frequency), will simultaneously emerge from the cell. Furthermore each collimated wave, being generated by a different temporal frequency component of the A-O drive signal, incurs a different Doppler shift caused by the moving grating in the cell, hence the collimated waves are mutually incoherent. Analogously to the spatially incoherent source described above we have a set of mutually incoherent plane waves, although with the A-O method each plane wave incurs a fixed Doppler shift whereas in the rotating ground glass source described above each plane wave is temporally modulated by a signal having a spread of frequencies given by the rotation of the diffuser.

The coherence imaging method described here becomes much clearer when the spatially incoherent illumination is generated Acousto-Optically. In this case each object spatial frequency component gets mapped to a unique temporal frequency. All the temporal frequencies can travel down the fiber in the same spatial mode while remaining separable due to their mutual incoherence. Although this is similar to wavelength multiplexing[2,3] the typical spectral broadening caused by the A-O will be < 1 GHz and the light can still be considered relatively monochromatic, hence the system is still best described in terms of spatial incoherence.

Experiments and results

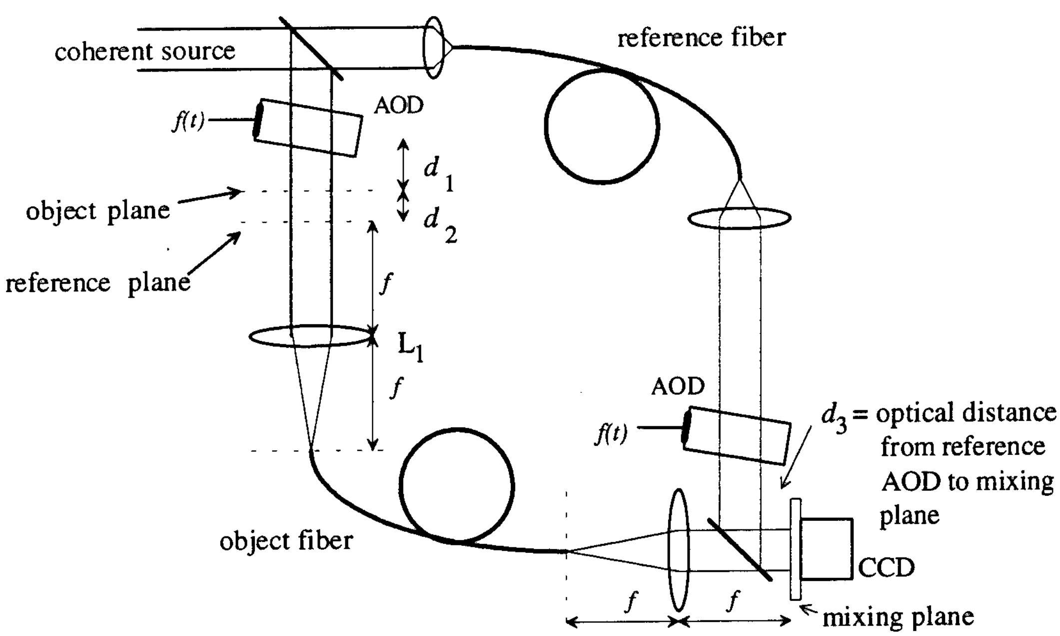
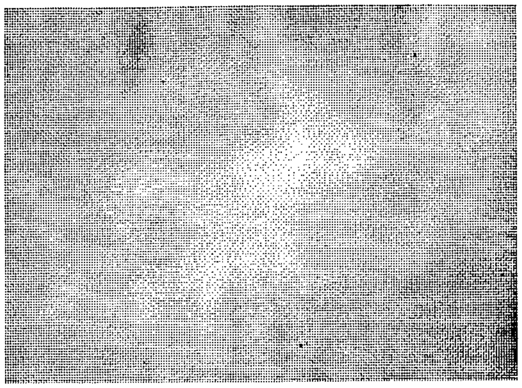


Fig. 3. Experimental setup for coherence imaging through optical fibers. AOD = Accousto- Optic deflector.

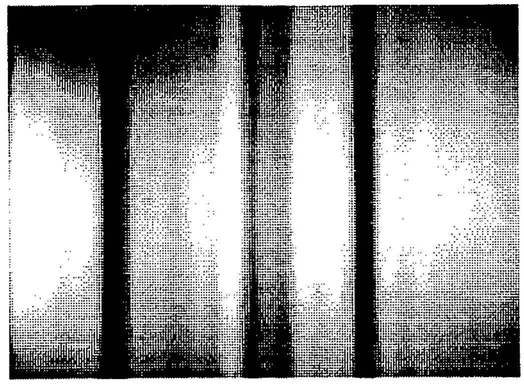
The experimental setup use is shown in Fig. 3. The effectiveness of this system was tested by sending 2-D (one lateral dimension and depth) images down a pair of Corion dispersion shifted 8 um diameter core fibers using He-Ne laser light and the system in Fig. 3. The A-O devices used were Brimrose slow shear TeO_2 deflectors (N = 520, Dn_s = 40 MHz, n = 2.25, V_s = 617 m/sec). The A-O cells were driven by a linear FM (chirp) signal with a bandwidth of 15 Mhz and a period less than the access time of the A-O cells. The object was a three bar pattern made up of 0.2 mm diameter wires laterally separated from each other by 1 mm. Furthermore, the middle wire was separated in depth from the two outside wires by a distance of 10 cm. The interference pattern at the mixing plane was recorded on a CCD camera and the images were electronically reconstructed. Figure 4a shows the transmitted image with the reference beam blocked and the A-O deflectors disabled. No imaging whatever of the wires is obtained, we are restricted by the classical resolution limit which for this case is ~7.5 mm. Figures 4b and 4c show two planes of the transmitted image obtained with the coherence imaging technique. Both of these intensity images were obtained from the same reconstructed complex (amplitude and phase) image. The focusing was also done electronically. Figure 4b shows the reconstructed image with the plane containing the outside wires in focus and Fig. 4c shows the plane containing the middle wire in focus. The horizontal ringing in Fig. 4c is caused by electronically focusing a finite size image. The theoretical resolutions, based on the A-O drive bandwidth (Dn_s) of 15 MHz, are ~0.1 mm for the lateral dimension and

~6 cm for depth. Experimental resolution are <0.2 mm and <10 cm for the lateral dimension and depth respectively. The system has performed near the theoretical resolution limit.

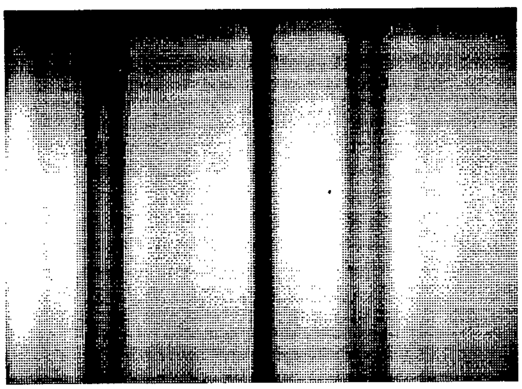
Another experiment involved full 2-D lateral imaging using the scanning method described above. In this case the object was physically scanned across 13 points along the y-dimension and the 2-D image was built up in the computer. Figure 5 shows the image obtained for an object made up of a pair of crossed wires (0.2 mm for the vertical wire and 0.5 mm for the horizontal wire).



(a)



(b)



(c)

Fig. 4. (a) Transmitted image with the reference beam blocked and the A-O deflectors disabled. Transmitted image using coherence imaging with the plane containing the (b)outside wires in focus (c) middle wire in focus.

Fig. 5. Two lateral dimension image transmitted through fiber using coherence imaging along the x-dimension and scanning along the y-dimension.

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